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Final Technical Report: NAG 5-1216

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Title: Wolf-Rayet Stars of WN Type

Summary

The following is the final report on NASA grant NAG 5-1216 to the University of Colorado for the project entitled "Wolf-Rayet Stars of WN Type". It covers the activities of the PI, C. D. Garmany, and the Co-PI, W.D. Vacca, as well as two graduate students who joined the project, P. Morris and K. Brownsberger. The grant covered partial salery support for Vacca and Morris as well as the purchase of a GraphOn terminal used by Vacca, and following the completion of Vacca's Ph. D., by Morris. Two papers have been published relating to this project, one paper has been submitted, and one paper is in preparation. In addition, Vacca completed his Ph. D. thesis in Dec. 1991. The list of papers supported by this grant is given at the end.

Description of the Research Project

Using *IUE* archival data in the wavelength range 1200 – 3200 Å, Vacca has have developed a new quantitative method of nulling the 2175 Å interstellar absorption feature observed in stellar spectra and has used this method to determine the color excesses and UV spectral indices for 44 Galactic and 32 Large Magellanic Cloud (LMC) Wolf-Rayet stars. In order to determine the most accurate values possible, we have chosen only those stars located in regions for which the reddening law is either well known or expected to be similar to the Galactic or LMC mean. Our method assumes that the intrinsic UV continuum of Wolf-Rayet stars can be well represented by a power law of the form $F_\lambda \sim \lambda^{-\alpha}$. Through the use of a χ^2-minimization technique, the method provides an objective determination of the color excess and its statistical error.

We have combined our values of color excesses with published line-free spectrophotometry to derive line-free intrinsic colors for Wolf-Rayet stars of nearly all spectral subtypes. In general, there is no correlation of intrinsic color or UV spectral index with spectral subtype for single WN and WC stars. This result agrees with previous suggestions that there is a large range in the values of intrinsic parameters for stars within a given Wolf-Rayet subtype. Our results demonstrate the need for a two-parameter spectral classification scheme for WN stars. We have compared our intrinsic colors with those predicted by current models of Wolf-Rayet stars and find generally good agreement. In addition, we find that the early WN stars in the LMC have smaller spectral indices and redder intrinsic colors than early WN stars in the Galaxy. We have also derived absolute magnitudes for the LMC Wolf-Rayet stars and those Galactic stars with reliable distance estimates. There is a clear separation in absolute magnitude between early and late WN stars. The values derived for Galactic WN stars are similar to those for LMC WN stars.

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Accurate color excesses are essential for the determination of the intrinsic parameters of Galactic Wolf-Rayet (W-R) stars. Intrinsic colors, intrinsic continuum spectra, and absolute magnitudes can be derived only if color excesses, $E(B-V)$, and the appropriate extinction laws are known. Knowledge of the intrinsic observational stellar properties (such as colors and magnitudes) is, in turn, fundamental to our understanding of the intrinsic physical parameters (such as radii and effective temperatures) and the evolutionary history of W-R stars. Theoretical models of the atmospheres of W-R stars incorporate values of the intrinsic observational quantities in order to deduce the physical parameters (see, e.g., Hillier 1987; Wessolowski, Schmutz, and Hamann 1988; Schmutz, Hamann, and Wessolowski 1989, hereafter SHW89) and comparisons of the observed properties with theoretical predictions provide stringent tests of the validity of the models themselves. In addition, reliable values of intrinsic colors and absolute magnitudes for Galactic W-R stars with measured color excesses and known distances are necessary for establishing possible correlations of these quantities with spectral subtype. Such correlations can be used to compute accurate distances to Galactic W-R field stars through the method of spectroscopic parallax (e.g., Smith 1968*c*; van der Hucht *et al.* 1988) and to compare with and/or derive the intrinsic properties of W-R stars in other galaxies and environments.

Unfortunately, there have been no systematic and consistent determinations of the color excesses of a large sample of Galactic W-R stars and this is one of the principal reasons why the values of their intrinsic stellar properties remain uncertain. Our present knowledge of the color excesses, intrinsic colors, and absolute magnitudes of W-R stars is based primarily on the work of Smith (1968*b*), Lundström and Stenholm (1984*b*, hereafter LS84), and Torres-Dodgen and Massey (1988, hereafter TM88). Smith (1968*b*) and TM88 studied W-R stars in the Large Magellanic Cloud (LMC), for which the distances are known and the color excesses (due to Galactic foreground reddening and reddening intrinsic to the LMC) have been estimated and, in general, are small. LS84 studied Galactic W-R stars that are members of open clusters and OB associations for which the distances are known; color excesses were estimated from other member stars near the W-R stars. Color excesses for several other individual Galactic and LMC W-R stars have been determined from a variety of methods. Van der Hucht *et al.* (1988) give a summary of some of the many independent calibrations of intrinsic color and absolute magnitude with W-R spectral type that have been derived from the various data sets and color excess determinations.

One direct method of determining the color excesses for Galactic W-R stars involves the "nulling" of the broad 2175 Å absorption feature observed in their ultraviolet spectra (e.g., van der Hucht *et al.* 1979; Nussbaumer *et al.* 1982; Garmany, Massey, and Conti 1984; Ford and Stickland 1986). This feature is a characteristic of the scattering of stellar light by the interstellar medium, probably resulting from the presence of graphite grains (e.g., Spitzer 1978, p. 158), and the depth of the absorption can be used to determine the amount of interstellar reddening along a line of sight. Typically, the nulling procedure involves correcting, or "dereddening," a stellar spectrum with an assumed extinction law and successively larger values of $E(B-V)$ until the absorption feature is removed, or "ironed out." Despite its relative simplicity and the abundance of UV data, no systematic and consistent application of this method to a large of sample of W-R stars has been made. In addition, when the procedure has been applied to individual stars, it has usually been performed in a rather subjective manner; color excesses determined by different authors for the same star using, in principle, the same method can vary widely. Furthermore, values of $E(B-V)$ have often been derived by applying an average Galactic reddening law to stars in various regions of the Galaxy, despite the fact that the reddening law may vary substantially from region to region.

In addition to the lack of reliable color excesses, previous determinations of the intrinsic colors and magnitudes of W-R stars have also been hampered by the presence of strong emission lines within the wavelength bands of optical filters. In order to reduce the emission line contributions to the flux values, Smith (1968*a*) adopted narrow-band ($\sim$ 100 Å wide) ***ubv*** filters for the measurements of W-R magnitudes. However, some emission lines are still included in the filter bands, and the line contamination is particularly bad for WC stars. Recently, Massey (1984) and TM88 measured the contribution of emission lines to the ***ubv*** magnitudes and determined line-free (or "monochromatic") apparent magnitudes and colors for most of the W-R stars in the Galaxy and the LMC. These data provide the best measurements to date of the stellar continua, uncontaminated by emission lines, for a large sample of W-R stars.

The ultraviolet spectra of the W-R stars used in this study were obtained from the archives of the *International Ultraviolet Explorer* (*IUE*) satellite; a description of the *IUE* satellite and its detectors is given in Boggess ***et al.*** (1978*a*, *b*). The stars and associated *IUE* images used in this analysis are listed in Tables 1 (Galactic W-R stars) and 2 (LMC W-R stars). The criteria used to select these stars are given below (§ III). All stars were observed in the low resolution mode ($\sim$6 Å), through the large aperture, with both the SWP (1150-2000 Å) and LWR or LWP (1850-3300 Å) cameras. All of the *IUE* images were corrected for temperature drift in the camera head amplifier (Thompson and Turnrose 1983; Thompson 1983) and all observations with the LWR camera were corrected for sensitivity degradation (Clavel, Gilmozzi, and Prieto 1986). The SWP images processed at Goddard before 1979 July or at VILSPA before 1979 August were recalibrated using the corrected intensity transfer function.

The UV spectra were extracted from the *IUE* images using the programs available at the *IUE* Regional Data Analysis Facility at the University of Colorado. In several cases, two or three well-exposed spectra for a star were averaged, each weighted by its exposure time. For several highly reddened stars, we spliced together two long wavelength (LWP or LWR) spectra

We have developed a new method of determining the color excesses for W-R stars in the Galaxy and the LMC. Our procedure is less subjective and more quantitative than previous methods and provides determinations of the statistical errors and the goodness of fit. It assumes that a power law of the form $F_\lambda \sim \lambda^{-\alpha}$ is a good approximation to the W-R UV continuum spectrum and uses a χ^2-minimization technique to determine $E(B-V)$. Using this method, we have determined color excesses for 44 Galactic and 32 LMC W-R stars. Our sample included only those stars located in regions where the extinction law is either well known or expected to be similar to the Galactic or LMC mean.

We find no correlation of UV spectral index or intrinsic color with spectral subtype for our samples of single WN and WC stars. This may be an indication that the current classification system for W-R stars needs to be replaced with a two-parameter scheme, particularly for WN stars. There is evidence that early WN stars in the LMC have flatter UV continua and redder intrinsic colors than early WN stars in the Galaxy. We find no separation between values derived for Galactic WC stars and LMC WC stars. We have compared our intrinsic colors with those calculated from model atmospheres of W-R stars and find generally good agreement. We have derived absolute magnitudes for W-R stars in the LMC and for those Galactic W-R stars located in clusters and associations for which there are reliable distance estimates. We find a clear separation between the absolute magnitudes of WNE and WNL stars. The Galactic values are similar to those derived for WNE and WNL stars in the LMC. Because of the lack of data for late WC stars we are unable to determine whether or not the absolute magnitude is correlated with spectral subclass for these stars.

Papers supported by this Grant

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